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The Voyager Interstellar Mission

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THE VOYAGER INTERSTELLAR MISSION*

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Abstract

The Voyage.r II~tcI-stellar Mission began on January 1, 1990, with the primary objective being, to characterize the interplanetary medium beyond Neptune and to search for the transition region between the interplanetary medium and the interstellar medium. At the start of this mission, the two Voyager spacecraft had already been in flight for over twelve years having successfully returned a wealth of scientific information about the plane. Ial-y systems of Jupiter, Saturn, Uranus, and Neptune, and the interplanetary medium between Earth and Neptune. With the two spacecraft having the potential to continue returning science data until the year 2020 there is a high likelihood of one of the two spacecraft penetrating the termination shock and possibly the heliopause boundary, and entering interstellar space..

'This paper describes the Voyager Interstellar Mission - the mission objectives, the spacecraft and science payload, the mission operations system used to support operations, and the mission operations strategy being used to maximize science data return even in the event of cer {sin potential spacecraft subsystem failures. The implementation of automated analysis tools to offset/enable reduced flight team staffing levels is also discussed

Introduction

The Voyager Interstellar Mission (VIM) is an extended mission having the potential of continuing spacecraft operations until around the year 20?(). This mission provides the heliospheric science community with an excellent opportunity to obtain in situ measurements of the. subsonic solar wind beyond the termination shock, and the interstellar medium beyond the heliopause boundary. Based on current estimates of the termination shock and heliopause locations, there is a high likelihood of a Voyager space.craft penetrating one or both of these heliospheric features before 2020.

The Voyage.r Interstellar Mission is characterized by:

(1) science requirements that can be satisfied with science instrument observations that are primarily repetitive in nature;
(?) long round-trip-light-times complicating spacecraft monitoring and contr 01;
(3) significantly reduced flight team staffing levels relative 10 the Voyager prime mission.

These mission characteristics have resulted in significant changes to the methods used to conduct both uplink and downlink mission operations. Changes have included the development of an entirely new sequence generation process consistent with the repetitive nature of the science instrument observations and the reduced flight team staffing levels. Ganges have also been made 10 the process used for real-tiil)c. monitoring of routine spacecraft operations. The development of an automated alarm monitoring tool has almost eliminated the need for real-time monitoring personnel. In addition, immediately after the start of VIM operations, the telemetry and command systems began a transition from project dedicated hardware and software to multi-mission hardware and software. This transition has been completed and the telemetry and command systems are now in a maintenance phase.

Throughout the 19 years of flight, the Voyager spacecraft operational/performance characteristics and the Ground Data System (GDS) capabilities have changed dramatically. In addition to the GDS transition to multi-mission hardware and software, periodic spacecraft and GDS configuration changes have been necessary to deal with:

(1) a better understanding of the actual spacecraft performance capabilities;
(2) spacecraft performance changes due to increased age or subsystem anomalies, anti;
(3) spacecraft engineering changes resulting from the ever increasing operating distance from the Earth and Sun.

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In addition, programmatic changes reducing the size of the flight team have had to be accommodated during VIM. The mission impact of the reduced flight team staffing has resulted primarily in limited reductions in science data acquisition and anomaly response capabilities.

Voyager Mission History

In the mid-1960s the basic plan for a multi-planet tour of the outer solar system planets with a single spacecraft was established. This plan relied on the use of the gravity field and orbital velocity of a planet to modify the trajectory of a spacecraft (gravity assist), permitting a single spacecraft to achieve multiple planet encounters without large on-board propellant requirements.[1] Pioneer 11, launched in 1973, was the first spacecraft to use a gravity assist to travel from one planet to another. The Pioneer 11 trajectory was targeted to achieve Jupiter encounter conditions that would bend the spacecraft's flight path and increase its heliocentric velocity enough to deliver it to Saturn.

The number of planets that can be reached using this gravity assist technique depends on the specific geometry of the planets positions. It was fortuitous that a rare (occurs approximately every 175 years) alignment of the outer planets, Jupiter, Saturn, Uranus, and Neptune occurred in the late 1970s that would allow a "grand tour" of all four giant planets by a single spacecraft. In 1972, the Mariner Jupiter/Saturn 1977 (MJS77) project was initiated to take advantage of this alignment (prior to launch the project name was changed to Voyager). MJS77 was a scaled down version of the potential four planet grand tour, initially being limited to conducting exploratory investigations of the Jupiter and Saturn planetary systems and the interplanetary medium between Earth and Saturn. In early 1976, the mission objectives were extended to include the possible Voyager 2 exploration of Uranus with an encounter in early 1986. The Neptune option was approved in 1985.

The Voyager 2 spacecraft was launched on August 20, 1977 and Voyager 1 on September 5, 1977. The launches were accomplish using the Titan III E Centaur D-1T launch vehicle. Voyager 1 having been launched on a higher energy trajectory passed Voyager 2 during the cruise to Jupiter, arriving at Jupiter first on March 5, 1979. Voyager 2 arrived at Jupiter four months later on July 9, 1979. From 1979 to 1989, Voyager 1 completed successful encounters with Jupiter and Saturn, and Voyager 2 completed successful encounters with Jupiter, Saturn, Uranus, and Neptune. Figure 1 illustrates the trajectories of the two Voyager spacecraft through the solar system and includes the closest approach dates at each planet

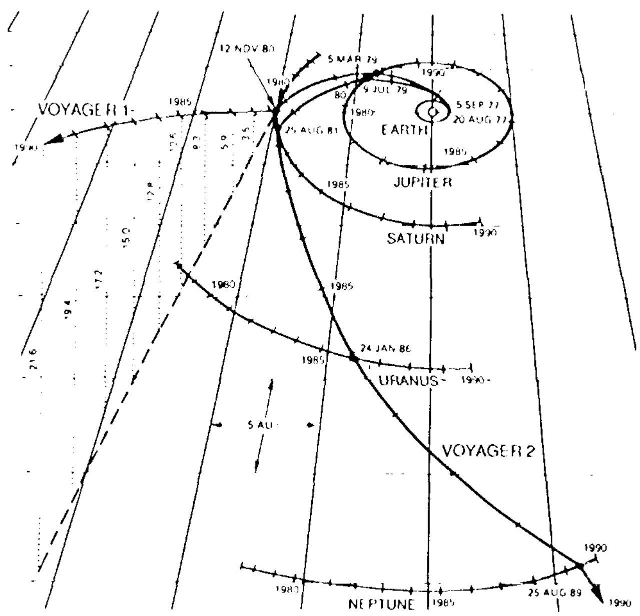


Figure 1 - Voyager 1 & 2 Interplanetary Trajectories

Voyager Spacecraft

Spacecraft Description

The two identical Voyager spacecraft are mechanized in hardware and software which, when operated by ground commanded sequences, are capable of making detailed scientific measurements for the exploration of the outer solar system. While the spacecraft hardware cannot be modified in flight, other than switching to redundant units, the software contained in the three on-board computers is capable of being reprogrammed. This reprogramming capability is a key Voyager spacecraft capability and has been extensively used, both during the Voyager primary mission and during the preparation for and conduct of the extended Voyager Interstellar Mission.

Because of the long round-trip-light-times involved throughout the Voyager mission, each Voyager spacecraft is capable of autonomous operation. This autonomous operation includes both the acquisition and transmission of science and engineering data to Earth, and in supporting an on-board capability to respond to a number of spacecraft anomalies with preprogrammed responses.

The Voyager spacecraft (825 kg including 103 kg of hydrazine propellant) is shown in its in-flight configuration in Fig. 2.[2]

Key spacecraft characteristics include:

- Three-axis stabilization: sun sensor, star tracker, 3-axis gyros;
- Two-degree-of-freedom scan platform;
- S-band uplink/downlink, X-band downlink;
- Polygon electronics bus structure: 10 bays;
- Radioisotope Thermoelectric Generator (RTG) power supply;
- Reprogrammable computers: Computer Command Subsystem (CCS), Flight Data Subsystem (FDS), Attitude and Articulation Control Subsystem (AACS);
- Hydrazine propulsion for attitude control and trajectory correction;
- Thermal blankets and louvered bays/assemblies;
- Digital Tape Recorder (DTR): 8 tracks, 536 megabits capacity;
- Six fields, particles and waves instruments;
- Five optical instruments, and;
- Radio science.

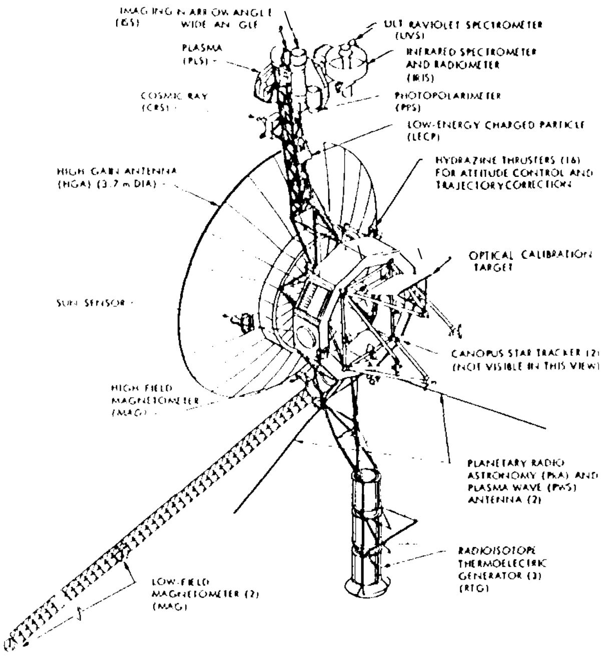


Figure 2 - Voyager Spacecraft

Over the course of the mission, periodic spacecraft and ground system configuration changes have been made as a result of either a better understanding of actual spacecraft performance characteristics, spacecraft performance changes due to increased age or subsystem anomalies, or engineering changes resulting from the ever increasing distance from the Earth and Sun. The most serious spacecraft performance change occurred on-board Voyager 2 in April, 1978, when its primary receiver and the tracking loop circuit on its back up receiver failed. This double failure meant that the uplink carrier reception capability of the spacecraft was reduced to a bandwidth of only ± 100 Hz instead of the normal ±100 KHz. This eliminated the receiver's capability for tracking the always present Doppler induced frequency validations in the uplink carrier signal. As a result of these failures, ground system modifications were implemented to provide the capability to vary the uplink carrier frequency transmitted by a Deep Space Network (DSN) tracking station in a manner that presented a near constant carrier frequency to the spacecraft receiver. The techniques developed in 197810 cope with this anomaly are still in use today. Key engineering changes resulting from a better understanding of the actual spacecraft performance and the ever increasing operating distance from the Earth and Sun are summarized in Table 1.[3,4,5]

Change	Benefit
1979 - Voyager 1&2 - Implemented image motion compensation using gyro drift turns	Allowed planetary limb tracking for radio science and target body tracking for close satellite flybys
1979 - Voyager 1&2 Implemented automated on-board DTR momentum cancellation capability	Reduced interaction between the DTR and resultant spacecraft motion
1985 - Voyager 2 - Qualified thrusters to operate at 4 msec pulses rather than the normal 10 msec	Reduced attitude control drift rate resulting in reduced image smear during long exposures
1985 - Voyager 2- Implemented on-board imaging data compression and Reed-Solomon data encoding	Allowed near Saturn-level volume of imaging data to be returned at Uranus and Neptune distances
1985 - Voyager 2 - Implemented increased gyro drift turn rate capability	Allowed image motion compensation for close Miranda flyby observations
1985 Voyager 2- Modified Parkes antenna for telemetry data reception arrayed with Canberra DSN antennas	Increased telemetry reception data rates at Uranus distance
1989 - Voyager 2 - DSN 64 meter diameter antennas enlarged to 70 meter diameter	Increased telemetry reception data rates at Neptune distance
1989 - Voyager 2- Modified Very Large Array (VLA) antennas for telemetry reception - arrayed with Goldstone DSN antennas	Increased telemetry reception data rates at Neptune distance
1989 - Voyager 2- Lengthened camera exposure duration capability	Needed to accommodate long exposure duration's at Neptune
1989 Voyager 2 - Implemented two new image motion compensation techniques long exposure duration at Neptune	Needed to minimize image-smear during long exposure duration's at Neptune

Table 1 - Summary of Key Engineering Changes

While both Voyager spacecraft have sustained partial engineering subsystem failures and performance degradation, each remains capable of supporting the Voyager Interstellar Mission objectives. Hardware redundancy and the ability to reprogram the on-board computers have provided adequate work-arounds for the anomalies experienced to date. However, as a result of partial subsystem failures, single point failure conditions do exist on each spacecraft.

For Voyager 1, a complete failure of one of the FDS computer memories resulted in a single-point-of-failure condition that would be mission catastrophic should the second memory fail. The FDS functions include control of all instrument operations, and the formatting of science and engineering data for transmission to Earth. The current FDS program utilizes essentially the complete remaining FDS memory. As protection against partial loss of the functioning memory, an FDS program has been constructed, with limited capabilities for instrument operation and data formatting, that requires only half of the FDS memory. In the event of a partial FDS memory failure, this program could be loaded into the functioning portion of the memory to continue Voyager 1 operations. A second Voyager 1 single-point-of-failure is in the Radio Frequency Subsystem where one of the X-band traveling wave tubes (X-TWT) has degraded to a near failed condition. The second X-TWT has been functioning continuously since 1989 without any indication of degradation.

For Voyager 2, the previously discussed receiver failure results in a single-point-of-failure condition which could result in the total loss of command reception capability. This potential failure has been offset by the on-board sequence capability (to be described) that will maintain science data acquisition until about 2020 even in the event of a failure of the remaining receiver.

Payload Description

During the Voyager prime mission, eleven science investigations were supported by twelve science instruments carried on-board each of the Voyager spacecraft.[6] Because of the nature of the VIM (a fields, particles, and waves mission), only seven of these instruments are appropriate for addressing the VIM science objectives. Table 2 identifies each of the payload instruments supporting the Voyager Interstellar Mission and provides a brief description of the instruments performance characteristics. All seven instruments, with the exception of the PLS on Voyager 1, are operating satisfactorily on both spacecraft. The PLS on Voyager 1 suffered a major loss of sensitivity shortly after the Saturn encounter. The instrument continues to operate in this degraded mode.

Instrument	Characteristics
Magnetometer (MAG)	Measures the magnitude and direction of magnetic fields between 0.006γ and 2X10[6]γ.
Low-Energy Charged Particle (LECP)	Measures intensities of charged particles with energies from about 30 keV to 100MeV for ions, and about 20 keV to >10 MeV for electrons. Provides spectral, angular, and compositional information about the particles.
Plasma Science (PLS)	Detects positive ions and electrons with energies-per-charge from 10 V to 6 kV. Provides plasma density, velocity, and temperature information.
Cosmic Ray Subsystem (CRS)	Measures the energy spectrum of electrons from 3 MeV to 110 Mev. Measures the energy spectra and elemental composition of all cosmic ray nuclei from hydrogen through iron over an energy range of ≈ 1 MeV/nuc through 500 MeV/nuc.
Plasma Wave Subsystem (PWS)	Measures the electric field components of local plasma waves over the frequency range extending from 10 Hz to 56 kHz.
Planetary Radio Astronomy (PRA)	Measures the spectrum, polarization, and time structure of radio emissions in the frequency range from 1.2 kHz to 40.5 MHz.
Ultraviolet Spectrometer (UVS)	Measures ultraviolet radiation in the 500Å to 1700Å range.

Table 2- Voyager Interstellar Mission Payload

The UVS remote sensing instrument is mounted on a movable two-degree-of-freedom scan platform. The other VIM instruments are body-mounted in a fixed orientation.

Voyager Interstellar Mission

Science Objectives

At the start of the VIM there were two science objectives being addressed;

(1) To investigate the interplanetary and interstellar media, and to characterize the interaction between the two, and

(2) To continue the successful Voyager program of ultraviolet astronomy.

Both of these objectives were supported from 1990 until 1993 when a programmatic change was made by NASA Headquarters deleting the ultraviolet astronomy objective. Ultraviolet observations continued after 1993, and are still being performed, but only in support of objective (1).

Specific science objectives currently being addressed and the investigations contributing to each objective are described in Table 3.

Science Objectives	Contributing Investigations
Characterize the evolution of the solar wind with increasing distance from the Sun	MAG, PLS, LECP, CRS, PWS
Observe solar cycle variation in the distant interplanetary medium	MAG, PLS, LECP, CRS, PWS
Investigate latitudinal variations in the interplanetary medium	MAG, LECP, CRS, PWS
Search for low-energy cosmic rays	LECP, CRS
Characterize particle acceleration mechanisms and plasma thermalization mechanisms in the interplanetary medium	MAG, PLS, LECP, CRS
Search for evidence of interstellar hydrogen and helium from the interstellar wind	UVS, PLS, LECP, CRS
Observe and characterize the termination shock of the supersonic solar wind	MAG, PLS, LECP, CRS, PWS, PRA
Characterize the subsonic solar wind beyond the termination shock	MAG, PLS, LECP, CRS, PWS
Observe and characterize the heliopause	MAG, PLS, LECP, CRS, PWS
Characterize the local interstellar medium and associated radio emissions	MAG, PLS, LECP, CRS, PWS, PRA, UVS
Observe radio emissions from the Sun and solar wind	PRA, PWS
Monitor the extreme ultraviolet emissions of the Sun	UVS
Search for interplanetary and interstellar gas	UVS

Table 3 - Science Objectives and Investigations

Trajectory Information

The two Voyager spacecraft are pursuing these science objectives from positions above and below the ecliptic plane. The Voyager 1 Saturn flyby resulted in the spacecraft being deflected out of the ecliptic plane to the north at an angle of 35.5° in the general direction of the solar apex. Voyager 2 was deflected by Neptune in a direction south of the ecliptic plain at an angle of 48° and about 90° away from the direction of Voyager 1. Figures 3 and 4 illustrate spacecraft heliocentric distance and heliocentric latitude (with respect to the ecliptic plane). Figure 5 indicates the distance each spacecraft is out of the ecliptic plane.

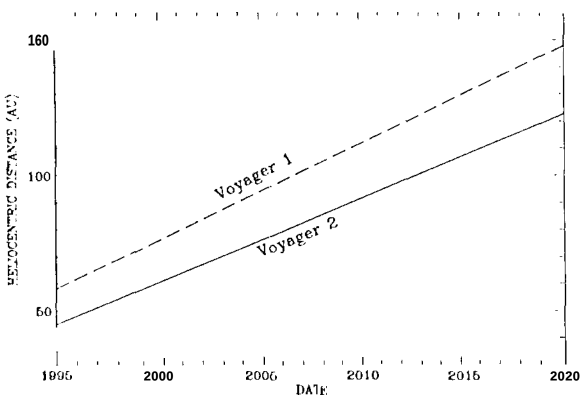


Figure 3 - Heliocentric Distance

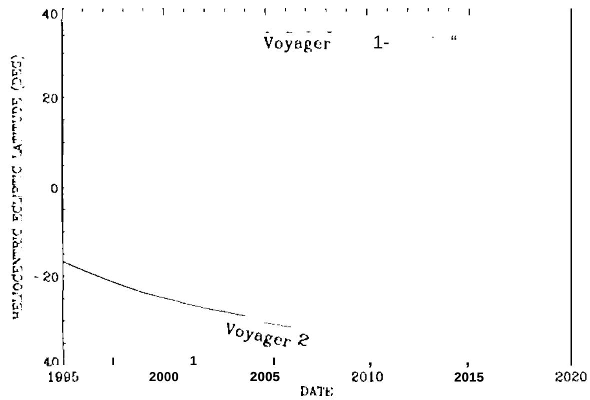


Figure 4- Heliocentric Ecliptic Latitude

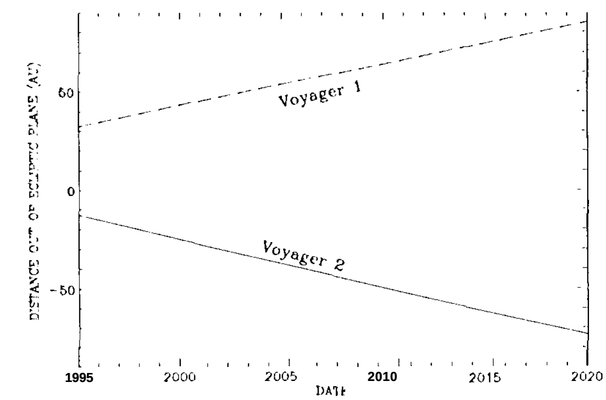


Figure 5 - Distance Out of Ecliptic Plane

Reaching the Termination Shock & Heliopause

Recent estimates, by the Plasma Wave Investigation Team, of the termination shock location range from 80 to 115 astronomical units (AU), and estimates of the heliopause location range from 110 to 160 AU.[7] The Cosmic Ray Investigation Team recently reported an estimate of the termination shock location in 1994 at 85 ± 5 AU.[8] Based on these estimates, reaching the termination shock and the heliopause with one of the Voyager spacecraft may be achievable within the projected lifetime of the spacecraft. Voyager 1 is currently 65 AU from the Sun, traveling at a speed of 3.6 AU per year, and will reach 150 AU in the year 2020. Voyager 2 is currently 49 AU from the Sun, traveling at a slower speed of 3.1 AU per year, and will reach 125 AU in the year 2020.

If the locations of these two heliospheric features are near the low end of these estimates, 80 AU (termination shock), 110 AU (heliopause), Voyager 1 would reach the termination shock in 2001, and the heliopause in 2009. Voyager 2 would reach the termination shock distance in 2006, and the heliopause distance in 2015.

Transition to the Voyager Interstellar Mission

The transition from the Voyager prime mission to the Voyager Interstellar Mission included significant changes in all areas of mission operations. Initially these changes included:

- greatly reduced flight team staffing consistent with an extended mission of reduced complexity;
- transition from project dedicated telemetry and command hardware and software to a multi-mission set of hardware and software;
- extensive re-engineering of the Mission Sequence Subsystem (MSS) to simplify the sequence generation process, and conversion where feasible from a main frame computer to a networked personnel computer (PC) based platform;
- configuration of the spacecraft FDS software to reflect the planned instrument operating modes and downlink data rates;
- development and implementation of the capability to store ≈ 30 years of High Gain Antenna pointing information in the CCS memory;
- implementation of a new spacecraft and instrument sequencing technique consistent with the repetitive nature of the planned science data acquisition strategy.

These initial changes were successfully accomplished in the 1990 - 1991 time period. During the 1992 - 1996 time period other significant changes have included:

- additional reduction (SO%) in flight team staffing size;
- initiated the transition of the complete set of MSS software to a UNIX platform, utilizing multi-mission core software where appropriate;
- developed and implemented automated alarm monitoring and notification capability to reduce the necessary real time mission control support.

Mission Operations System

The Voyager Mission Operations System (MOS) is the collection of hardware and software, facilities, personnel, and procedures utilized to remotely monitor and control the Voyager spacecraft and deliver data products to engineering and science users. Included in the MOS are the GDS, which makes extensive use of institutionally supported multi-mission ground data system elements, the Voyager flight team, and a mature collection of operating procedures that have evolved throughout the mission.

Ground Data System

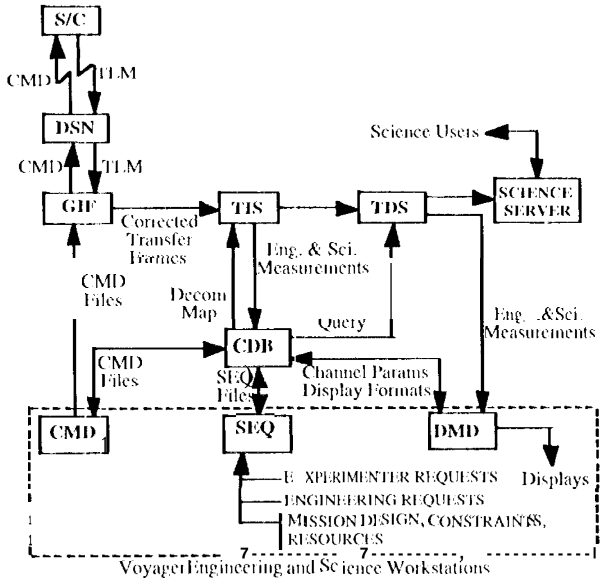
During the Voyager missions to Jupiter and Saturn, and then on to Uranus and Neptune, the GDS was frequently modified to incorporate capabilities based on new mission requirements, and to add performance enhancing features. However, the overall architecture of the GDS remained largely unchanged from launch, and was based largely on customized mission-dedicated processors for most real-time functions (i.e., telemetry, command), and batch-oriented mainframe processing for support of nonreal-time functions (i. e., sequencing, navigation, experiment records generation). As Voyager entered the VIM era the Project planned significant changes in how mission operations would be conducted. These plans included the reduction or elimination of some GDS support requirements and the addition of new requirements to support a completely re-engineered sequence generation process. This coupled with a decision to eliminate mission-dedicated systems in favor of new multi-mission capabilities led to a major overhaul of the GDS. A summary of GDS modifications since the beginning of VIM is provided in Table 4:

GDS Subsystem	Modifications Undertaken
Telemetry	Eliminated Univac and Vax-based mission unique hardware and software, and transitioned to Advanced Multi-Mission Operations System (AMMOS) for support of all real time telemetry processing.
Command	Eliminated mainframe-based translators and transitioned to AMMOS for support of command translation and ground command file generation.
Tracking	Eliminated requirements for support of this subsystem.
Navigation	Eliminated requirements for support of this subsystem.
Sequence	Eliminated mainframe-based sequence subsystem and replaced with a networked-PC system. Software completely redesigned to support new sequence generation strategy.
Spacecraft Analysis	Eliminated mainframe-based processing components and special purpose processors. Adapted AMMOS capabilities for spacecraft analysis support.
Data Records	Eliminated mainframe-based system and replaced with a file server architecture. Replaced old data records software with a mixture of AMMOS software and new customized software capabilities.
Imaging	Eliminated requirements for support of this system

Table 4 - VIM GDS Modifications

Today, the subsystems that comprise the Voyager GDS are the Telemetry, Command, Sequence, Spacecraft Analysis, and Data Records. These subsystems are distributed across the globe, from the DSN tracking stations to the facilities at the Jet Propulsion Laboratory (JPL). The GDS core processing elements are of the same lineage as those supporting Cassini, the Mars program, and other new missions, and are kept current through an active test program providing periodic GDS upgrades.

Connectivity between the DSN stations and the local GDS at JPL is accomplished via the Ground Communication Facility (GCF). Network communication links providing mission support include a "critical" Local Area Network (LAN) which connects all Voyager-resident elements (approximately 25 UNIX workstations) of the GDS. This LAN is connected across a gateway to the GCF and to the DSN tracking stations, and is the carrier of incoming spacecraft telemetry and science data, and of outgoing command traffic. Connected to this LAN are all the multi-mission components of the GDS, as well as other gateways leading to other projects and their mission-dependent LANs. Figure 5 provides an overview diagram of the Voyager GDS.



MOS SUBSYSTEM TERMS

CDB - CENTRAL DATA BASE SUBSYSTEM
CMD - COMMAND SUBSYSTEM
DMD DATA MONITOR AND DISPLAY SUBSYSTEM
GIF GROUND COMMUNICATIONS FACILITY INTERFACE SUBSYSTEM
SEQ SEQUENCE SUBSYSTEM
TDS - TELEMETRY DELIVERY SUBSYSTEM
TIS - TELEMETRY INPUT SUBSYSTEM

Figure 5- Voyager GDS

AMMOS telemetry processing elements (GIF, TIS): (1) detect and remove frame and packet format structures; (2) remove data transport artifacts and data redundancy, and; (3) provide recovery from lost, noisy and disorganized data. Data are broadcast over the LAN to project workstations in real-time and also stored in the CDB for later access. Workstation access to retrieve non-real-time data uses the data retrieval tools DMD and TDS.

The Voyager Data Records Subsystem (DRS) has evolved from a project-unique mainframe processing system to a workstation-based server capability. The DRS "science server" is connected to flight-critical portions of the GDS through a gateway to satisfy security requirements. Connection in this manner allows the science community timely and uncomplicated access to science processing functions, stored data, standard displays, etc. The server processes raw science and instrument health monitoring data, and provides short term data storage. The server supports the generation of Experiment Data Records (both quick-look and final) which are electronically transferred to the science team institutions.

The Sequence Subsystem relies on a mixture of Voyager-unique and multi-mission sequence generation software. All components of the MSS have transitioned, or are in the process of transition to UNIX platforms. The Voyager-unique components provide for sequence block parameter definition & editing, sequence construction and sequence validation. Multi-mission components interface to the fully multi-mission Command Subsystem where command generation, translation, transfer to a DSN station and radiation to the spacecraft occur.

It was mentioned earlier that Voyager actively pursues a testing program to maintain currency with the latest multi-mission capabilities. This is accomplished with the use of a test bed where new software is installed and basic capabilities tested in a flight-like environment. The Voyager test bed is typically composed of several flight workstations and a file server. The test bed configuration is transitory, and at completion of any test activity, workstations are reconfigured for flight support using the current operational version of GDS software.

Flight Team Organization and Staffing

The Voyager flight team organization has evolved from a multi-team organization at the start of the VIM to the current single team organization. Initially, the flight team was organized along functional lines with a Sequence Team, Spacecraft Team, Science Team, Mission Control Team, Navigation Team, and a Data Management Team. With a staffing level of about 50 people, including management functions, flight team members tended to specialize in specific technical areas. There was some, but limited cross training of people to perform multiple functions.

With the staffing reduction in 1993 to a flight team level of about ?5 people, the organization and the level os cross training changed significantly. The organization became process oriented with only two teams, an Uplink Team and a Downlink Team. The Navigation Team, consisting of one person, was eliminated at this time because of the stability of the orbit determination solutions and a trajectory estimate that would satisfy the mission requirements for the duration of VJM. The Uplink Team had responsibility for all functions necessary to generate spacecraft event sequences and command loads, and to transmit and confirm commands sent to the spacecraft. The Downlink Team had responsibility for the captain, conditioning, and delivery of science and ancillary data committed by the project to the science teams, as well as all engineering data required for monitoring the status of the Voyager spacecraft. The Downlink Team also performed analysis of engineering telemetry data to determine spacecraft and instrument performance and health. It also provided inputs to the uplink process for the development of spacecraft sequences to obtain the necessary engineering data to evaluate spacecraft and instrument performance and health. The Downlink Team also provided spacecraft state and status data to predict spacecraft behavior for real time monitoring. With the two team organization and 25 member flight team, the majority of flight team personnel had responsibilities on both the Uplink Team and the Downlink Team with team personnel cross trained to perform multiple operations functions. This cross training, combined with the deletion of selected lower priority operations tasks, was essential to accomplishing the necessary functions with the limited personnel available for mission operations support.

With an expected further reduction in flight team staffing in 1998 to 16 - 18 members, the flight team was reorganized in mid 1996 to a single team organization. While the staffing reduction is not anticipated before mid 1998, this early change will provide valuable experience before the staff down occurs. Additional cross training and combining of functions will be necessary to assure all necessary operational functions are performed. Figure 6 describes the single team organization and the major functions performed by the flight team.

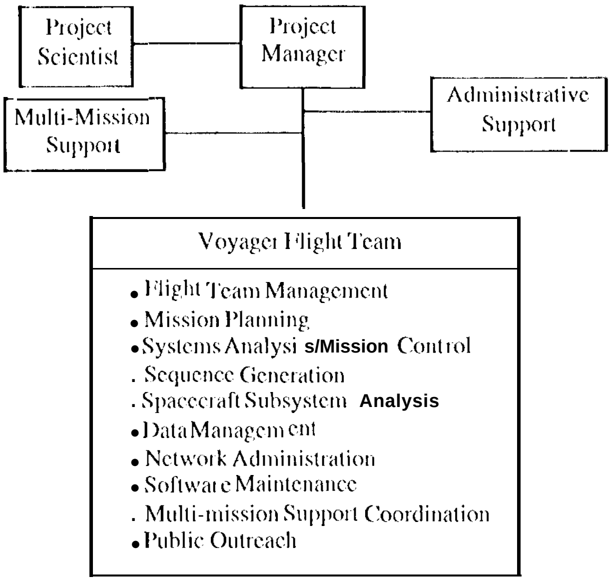


Figure 6 - Voyager Project Organization

Mission Operations

Data Acquisition and Delivery

Data acquisition and delivery is the payoff for any space science mission. It consists of all ground and spacecraft operations necessary to perform the desired science observations, transmission of the science data to the ground, capturing the data on the ground, processing the data, and delivering it to the science investigation teams for their analysis.

Sequencing Strategy

Key to acquiring the desired science observations and maintaining an adequate level of mission adaptivity is the sequencing strategy. Because of the limited flight team resources available for spacecraft sequence generation, this strategy has to minimize the labor required while satisfying the science data acquisition requirements and flight system health and safety engineering needs.

The sequencing strategy employed for the VJM is quite different from the strategy used during the Voyager prime mission. During the prime mission (pre-1990), the sequencing strategy involved periodically sending a group of commands (command load) to the spacecraft that would control its operation for a specified period of time. This time period could be as much as a few months during the cruise between planets, to as little as several hours scar the spacecraft's closest approach to a planet. The command load reflected the desired spacecraft sequence-of-act ivities (sequence). These sequence-o f-activities were, in general, a series of one of a kind instrument observations, with each sequence being unique in nature. Because of the frequency of command loads and the complexity and uniqueness of (tic sequences, Several sequences/comm and loads would be in development at the same time. This concurrent sequence development effort required a large Sequence Team to generate and validate the multiple spacecraft sequences/com mand loads.

In contrast, the V 1 h 4 science objectives and resulting instrument observations, along with the limited flight team staffi ng led to a very diflc.rent sequencing strategy for the VIM. Instead of one of a kind activities, the VJM is characterized primai ily b y repetitive science observations.

In response to t h i s fundamental change in observation requirements, a sequencing strategy comprised of four basic elements was devised and implemented in the first year of the VJM (1990). The fi st ele me nt of this strategy is a continuously executing sequence o f repetitive science observations and eng ineering calibrations called the "base.lim sequence." A basel ine sequence is stored on-board each spaceci aft and cont ains the instru ctions needed to acquire and return the basic fields, particles and waves science data to the ground. This sequence will continue to execute for the duration of the mission without any additional commands from the ground

The second element of the strategy is having the pointing information necessary to keep the boresight of the 1 ligh Gain Antenna (HGA) pointed at the 1 {arth until the year 2020 for Voyager 1 and 2.()17 for Voyager 2 stored (m-board each spacecraft. This provides the capability for continuous communication with each spacecraft without further HGA pointing commands,

The third element provides the capability of augmenting the baseline. sequence with non-repetitive science or eng ineering events using either an "overlay sequence," or a "mini-sequence." The difference between these two types of augmentation sequences is that the overlay sequence operates for a fixed interval of lime, currently 6 111011 ()1s, and contai ns al I of the baseline sequence augmentations for that time interval. A mini - sequence is focused on accompl ishing a single augmentation need and i s not a regularly scheduled activity but is done on an as-needed basis.

The fourth element is the use of pre-defined and validated blocks of commands (high level sequencing language), rather than the optimized sequence of individual commands (low level sequencing language), used during the prime. mission to accomplish desired spacecraft functions. While the USC. of pre-defined blocks of commands greatly reduces the effort required to generate and val idate a sequence of commands, there is an inefficiency in the number of memory words needed to accomplish) a given function. Fortunately, the VIM science data acquisition req uirements and available on-board sequence storage memory supports the use of pre-defined blocks of commands.

Baseline Sequence

The baseline sequence is the set of instructions stored in the CCS memory and composed of the repetitive spacecraft activities that execute continuously to return the basic fields, particles, and waves science data. 1 {leven predefined spacecraft block routi nes (equivalent 10 software subroutines) also stored in the CCS memory arc used by the baseline sequence to accomplish the desired spacecraft activities. During normal operations, each spacecraft perfori ns the following repetitive baseline. sequence science and engineering activities:

- continuous collection and return of cruise science data al 160 bps;
- weekly recording of one frame of high rate plasma Wave data;
- playback of si x months of recorded high rate plasma wave data every 6 months;
- execution of a magnetometer calibration roll maneuver (M AGROL) every 3 months;
- execution of a High Gain Antenna/Sun Sensor calibration maneuver (ASCAL) every 6 months;
- execution of a monthly Fields, Particles and Waves Periodic Engineering and Science Calibration (PMPCAL);
- perform DTR maintenance twice a year;
- perform gyro conditioning and a CCS timing test every 3 months.

Overlay/Mini-Sequence

Overlay sequences are Used to augment the continuously executi ng baseline sequence and are prepared on a regularly scheduled basis, currently every 6 months. The overlay sequence provides a mechanism for incorporating non-repetitive science and engineering events into the spacecraft scqucncc-of-activities and executes in combination with the baseline sequence. Typical events in overlay sequences have included:

- ultraviolet stellar and heliospheric observations;
- two additional MAGROLs per year per spacecraft;

- additional high rate plasma wave records and playbacks;
- DTR playbacks to recover data when a baseline sequence playback is not captured on the ground
- updates to the Backup Mission Load or Fault Protection Algorithms;
- updates to the baseline sequence.

During the first three years of the VIM, overlay loads were generated every 3 months for each spacecraft. One of the effects of the 1993 flight team staffing reduction was the extension of the overlay load duration from 3 months to 6 months. The most significant science data acquisition impact of this extension was the effective halving of' the acquisition of ultraviolet data at different scan platform positions throughout the year.

The acquisition of ultraviolet observations, which requires pointing of the scan platform, is the primary driver for the regularly scheduled overlay loads. Around the turn of the century, the available electrical power will no longer support the operation of the scan platform and the ultraviolet instrument. At that time, the use of overlay sequences will probably end and mini-sequences, prepared on an as needed basis, will be used to augment the baseline sequence. Mini-sequences are usually intended to perform a single specific function rather than the multiple functions performed by an overlay sequence. A mini-sequence may be used to replay DTR playback data not captured on the ground, respond to a spacecraft anomaly, record and playback additional high rate plasma wave data when the termination shock is encountered, or other science or engineering activities.

Transmitting the Data to the Ground

The Voyager Interstellar Mission is, with one exception, a real time data acquisition and return mission. All seven of the operating instruments on each spacecraft are continuously collecting data and transferring it to the FDS for immediate transmission to Earth. The normal real time transmission data rate is 160 bits per second (bps), including 10 bps engineering data. Periodically the real time data rate is increased to 600 bps to provide increased ultraviolet spectral resolution during solar monitoring observations.

The one exception to real time data return is that once a week on each spacecraft, 48 seconds of high rate (115.2 Kbps) of plasma wave data are recorded onto the DTR. These data are played back every 6 months providing increased temporal and spectral resolution snapshots of the plasma wave information. These high rate plasma wave data have provided the primary data for the Plasma Wave Investigation Team's estimate of the termination shock and heliopause locations. " Recording and playback of high rate plasma wave data will continue until the years 2010 (Voyager 1) and 2012 (Voyager 2) when telecommunications capability will no longer support the minimum playback data rate of 1.4 Kbps.

Capturing the Data on the Ground

Real time telemetry data capture is accomplished using 34 meter tracking antennas of the DSN. Capture of the high rate plasma wave data, requires the use of 70 meter tracking antennas, and in some instances a two antenna array of a 70 meter and a 34 meter antenna.

Science investigation teams would like to have contiguous data capture ('24 hours per day of tracking support for each spacecraft) to maximize there ability to characterize the heliosphere and the heliospheric processes that are at work in the outer solar system. Continuous tracking support is unrealistic given the number of current and future spacecraft utilizing the DSN's antenna resources. Sixteen hours per day of tracking support for each spacecraft is the project's target for science data acquisition. This target has been achievable in the past but the expected future increase in missions being supported by the DSN networks will result in reduced tracking station availability for the two Voyager spacecraft. As tracking support is reduced. the ability to characterize the heliospheric medium is degraded. Acceptable minimum science data acquisition requirements vary between 12 and 4 hours per day per spacecraft depending on the specific investigation.

Delivery to Science Investigation Teams

Science data are provided electronically to the science investigation teams in the form of a Quick Look Experiment Data Record (QEDR) and Experiment Data Record (EDR). A Voyager 1 and Voyager 2 QEDR for each science investigation is generated daily (Monday through Friday) containing the available. data since the last QEDR was produced. Since. these products are produced in near-real-time, generally within 24 hours of the data capture, data gaps due to a variety of ground problems can be present in the QEDR product. Once a week (Thursday), EDRs are created for the previous weeks (Thursday through Wednesday) data capture. In this product, data gaps resulting from ground problems have been filled to the extent possible. When the final EDRs are available, science teams are notified by electronic mail. The science teams then retrieve the data at their convenience for further processing and analysis.

Spacecraft Monitor and Control

Spacecraft monitor and control includes the real-time. functions necessary to monitor spacecraft health (downlink functions) and to transmit and verify commands (uplink functions). During the primary Voyager mission these real-time functions were supported around the clock by flight team personnel. With the reduced flight team staffing during VIM and the accept abi lily of increased risk daring an extended mission, real-ti]m support is limited to weekday prime shi ft and special off-shift events (commanding, I)TR playbacks, and attitude maneuvers). This reduced real-time monitoring support was enabled by the development and implementation o f an automated telemetry monitoring tool. This tool, VAMPIRE (Voyager Alarm Monitor Processor Including Remote I :xaminat ire), processes the broadcast telemetry data, detects alarm conditions, and initiates contact with on-call personnel who may remotely log onto the engineering workstation via a secure dial-back modem to evaluate the telemetry data when anomalous conditions occur. '1 'his automat ion tool has proved to be valuable in maintaining high mission reliability during significant downsizing of the flight team staffing level.

Maintaining Spacecraft Health and Safet y

While spacecraft monitor and control is a real-time operations function, maintaining spacecraft health and safety is a non-real-time function. 11 includes: the analysis of eng ineering telemetry data to establish and evaluate subsystem performance treads; the. periodic inflight execution and analysis of subsystem calibrations and engineering tests; the identification and analysis of anom alous conditions and the determination of recommended corrective actions.

The analysis o f engineering telemetry data to establish and evaluate subsystem performance trends is a regularly performed operations function. The UNIX workstations provide tabular and graphic summai ics of real-time o r archived telemetry data. } lowever, the analysis of these data relies on the system and subsystem expertise retained by the individual flight team members. A s the flight team looses system and subsystem cxpc]-list due to the retirement of flight team members and the downsizing of the flight team, it is imperative that automated analysis (()()1s be implemented. A n effort is currently underway within the flight t e a m to identify potential automated subsystem analysis tools for fut ure implementation.

Periodic inflight calibrations and engineering tests arc used for verifying spacecraft performance, and maintaining spacecraft capabilities. While some of these calibrations and tests are included in the baseline sequence, the majority arc initiated from the ground in either an overlay sequence or a mini-sequence.

The identification and analysis o f anomalous conditions and the determination of recommended corrective actions is a function that is performed wl ienever needed. It's accomplishment is similar to the analysis o f engineering telemetry data, in that it relies on the system and subsystem expertise of the individual flight team members. To assist the CC 'S/I 'DS analyst, there is an automated tool, MARVEL. (Monitor/Analyzer of Real-time Voyager Engineering I .ink) that monitors CCS/FDS telemetry data and displays on a workstation screen any conditions that are not as predicted. MARVEL performs limited analysis of the CCS/FDS telemetry and identifies possible. causes of the anomalous condition and potential corrective actions from the stored knowledge base within the program.

Consumables Management

Both spacecraft have on-board consumables that are adequate to support spacecraft operation until around the year 2020." I 1 ydrazine propel lant, for attitude control, and electrical power arc the two major consumables. 1 3oth spacecraft have over 35 kg of hydrazine which pi ovide over 50 years of operation at the current usage. rates.

f :lectrical power for t he Voyager spacecraft is provided by RTGs which at launch provided ≈ 470 watts of electrical power al 30 Vdc. 1)ue to the radioact ive decay of the plutoni um fact source, the electrical power provided by the RTGs is continually declining. 1 'he current rate of decay is approximately 5.2 watts per year. In order to maintain an adequate power margin, it is necessary to periodicall y reduce the spacecraft's power usage, by turning off power loads. '1'able, 5 summarizes the key mission changes resulting from the power reduction plan. This plan preserves the operation of the fields, particles and waves instruments (MAG, 1'1,S, LECP, CRS, PWS, PRA) until approximately 2015 at which time they will be turned off, one at a time, as necessary. The order of turn-off wi ll be dependent upon the instrument stat us at that time.

Power Reduction	Voyager 1	Voyager 2
Terminate UV data acquisition and scan platform operations	1999	1998
Terminate gyro operations (MAGROL & ASCAL calibrations)	2007	2004
Start turning off fields, particles and waves instruments	2015	2016

'1'able 5 - Key] 'owcr]< c(iLlclioll];Y' ct]ls"

Mission Adaptivity

While Voyager is primarily a real-time data acquisition and return mission, two types of science data acquisition and return adaptivity exist. Both of these capabilities have been successfully used during the VIM.

The first Or these capabilities is the recovery of a high fate 1'WS playback that is not captured with the initial playback. The response to the loss Or a playback is 10 sequence a second playback prior to the time when data on the. DTR is overwritten with newly recorded data. For normal baseline sequence recording of PWS data this allows 6 11101111)s to execute a second playback.

The second of these capabil it ies is to increase the frequency of high rate PWS records and playbacks. '1 'his can be i n response to a predicted termination shock crossing or increased plasma wave activity during cruise. Increased plasma wave activity in 1992 and 1993 resulted i n increasing the record and playback rate to improve the temporal resolution of the observed event.

Protection Against Spacecraft Failures

I n 01 der to maxi mize the spacecraft science data return reliability for an extended mission with the potential of continuing until 20?(), automated safeguards against possible mission-catastrophic failures are provided by each Voyager spacecraft. These safeguards include the Backup Mission Load and automated Fault Protection Algorithms.

Backup Mission Load

The first of these safe.gLmrds is the Backup Mission Load (BML) which provides on-board automated protection ag ainst the loss of command reception capability. This is especially important r_{ol} Voyager 2 where the primary receiver has already failed resulti ng in a singl e-poi nt-of-failure condition. Without command reception capability, the spacecraft must continue to operate with the instructions previously stored in the CCS memory. The BML reconfigures the spacecraft for maximum telecommunication and attitude control reliability and modifies the base.line sequence to continue the acquisition and transmission of fields, particles, and waves science data as long as the spacecraft continues to function. K c y BML changes to the spacecraft configuration and baseline sequence include:

- selection of attitude control deadband to maximize downlink telecommunications capability;
- increase yaw thruster pulse duration from 4 msec to 10 msec (return to normal duration);
- selection of the 160 bps data rate for ma-lime telemetry data return;
- selection of X-band high power for downlink telemetry data transmission;
- termination of attitude maneuvers (MAGROLs and ASCALs).

The BML will also terminate gyro operations al specified t i m e s when the predicted electrical power availability will no longer support their operation (2007 for Voyager 1 and 2004 for Voyager 2). DTR record and playbacks will also be terminat ed by the BML when the predicted downlink telecommun ications performance will no longer support the playback rate of 1.4 kbps (2010 for Voyager 1 and 2012 for Voyager 2).

Fault Protection Algorithms

Each Voyager s p a c e c r a f t has Fault Protection Algorithms (FPAs) stored on-board that are designed to rL'L'over the spacecraft from otherwise mission-catastrophic failures. The FPAs am mostly implemented in the CCS, while a few a r c interactive with t h e AACS fault protection routines. '1'able 6 describes the five FPAs that are stored in the CCS.

FPA Name	FPA Description
AACS Power Code Processing	Monitors AACS status information and issues pre-progr am med recovery responses in the event of AACS anomalies
Command Loss	Switches to redundant command reception hardware units in an effort to re-establish com mand reception capability if a command has not been received within a specif ied time interval (currently set at 42 days)
Radio Frequency Power Loss	Monitors S and X-band exciter and transmitter hardware, and switches to redu ndant units if a failure is detected
CCS Err[11	Responds to critical anomalous CCS hardware and software conditions. The response typically stops any on-going sequence activities, places the CCS in a known quiescent state and waits for ground action
Power Recovery	Responds to CCS tolerance detector trip or spacecraft undervoltage power utilization condition by switching to redundant hardware in an atte mpt to isolate an electrical fault and then eliminating power loads in a predetermined man ner if required

Table 6 - Fault Protection Algorithms

Voyager Project 110MC. Page

For more information and the current status of the Voyager Project, the World Wide Web address of the Voyager Project Home Page is

http://vrapt or.jpl.nasa.gov/voyager/voyager.html

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References

1. Cesarone, R. J., A Gravity Assist Primer, AIAA Student Journal, Spring 1989.
2. Heacock, R. L., The Voyager S/C, Proceedings of the Institution of Mechanical Engineers, Volume 194 No. 28.
3. Marderness, H. P., Voyager Engineering Improvements for Uranus Encounter, AIAA/AAS Astrodynamics Conference Paper W-2 110, Williamsburg Virginia, August 18-20, 1986.
4. McLaughlin, W. I. and Wolff, D. M., Voyager Flight Engineering: Preparing for Uranus, AIAA 23rd Aerospace Sciences Meeting Paper 85-0287, Reno Nevada, January 14-17, 1985.
5. Miller, L. J., Savary, K. E., Voyager Flight Engineering Preparations for Neptune Encounter, AIAA/AAS Astrodynamics Conference Paper 88-4263-CP, Minneapolis, Minnesota
6. Voyager Project, Special Issue, Space Science Reviews, Volume 21 No. 2 (Nov 1977), and No. 3 (Dec 1977).
7. Kurth, W. S., D. A. Gurnett, A Low-Frequency Wave Investigation For An Interstellar Probe Mission, Proceedings of the First IAA Symposium on Realistic Near-Term Advanced Scientific Space Missions, June 25-27, 1996.
8. Stone, E. C., A, C. Cummings, The Distance to the Solar Wind Termination Shock in 1993 and 1994 from Observations of Anomalous Cosmic Rays, Journal of Geophysical Research, vol 101, p11017, 1996.